NuMI

MINOS

NuMI Off-axis
Beam, Systematics, Background

Outline:

1) Brief description of NuMI beamline, construction status, on-axis beam to MINOS

2) Kinematics that lead to off-axis beam

3) ν_e beam background

4) Prediction of far off-axis spectrum from near detector measurement

5) Anti-neutrino running

6) Is another near detector useful ?

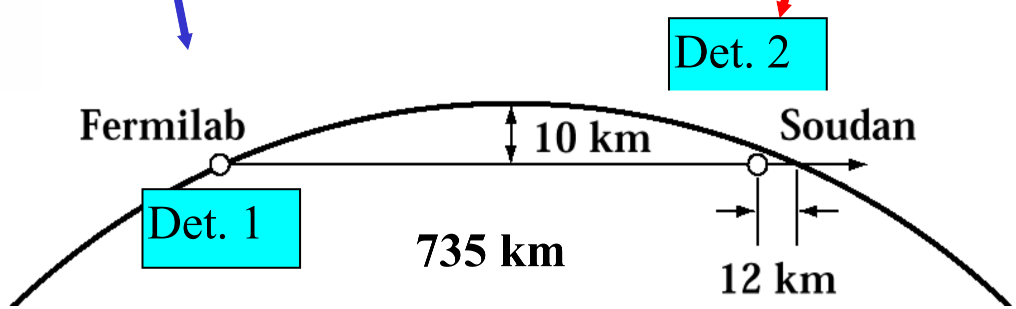
7) Further optimization of beamline ?

MINOS Experiment

Two Detector Neutrino
Oscillation Experiment
(Start Dec 2004)

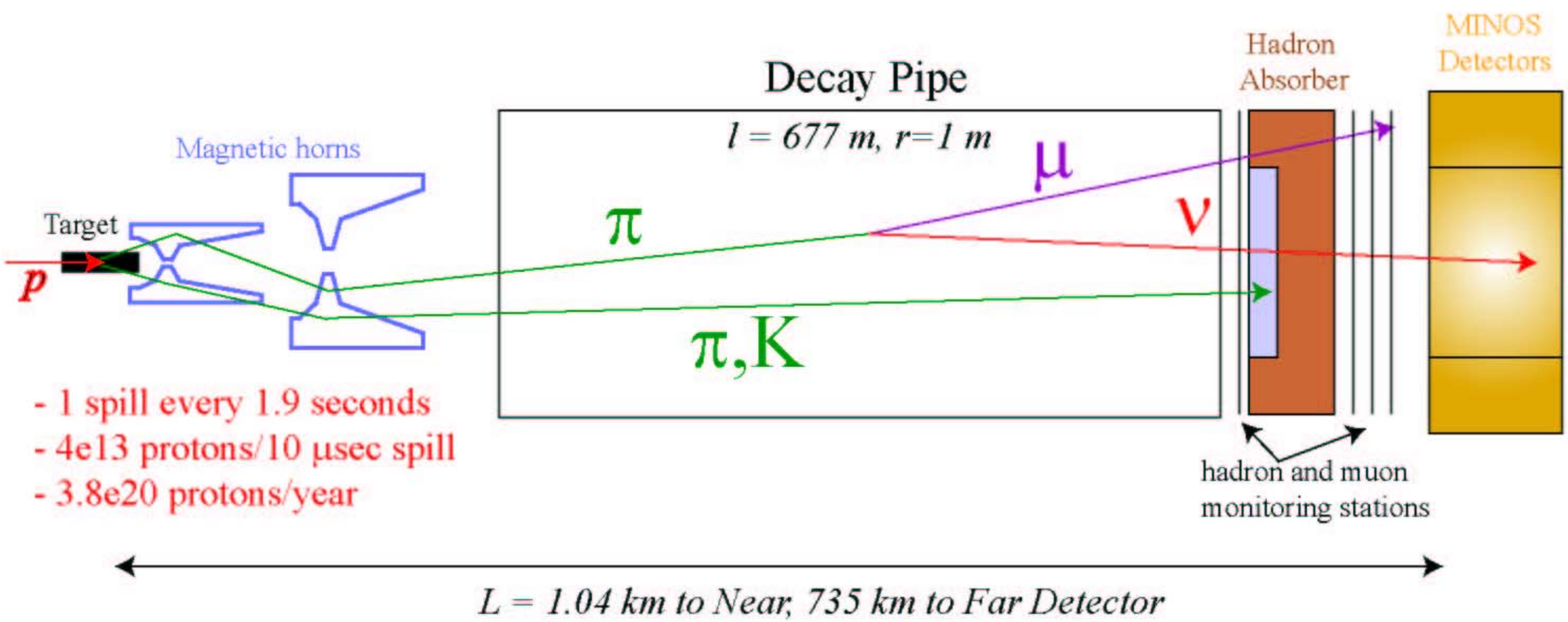
Near Detector: 980 tons

Far Detector: 5400 tons



How ν beam is produced

120 GeV/c protons strike graphite target
  Magnetic horns focus charged mesons (pions and kaons)
    Pions and kaons decay giving neutrinos

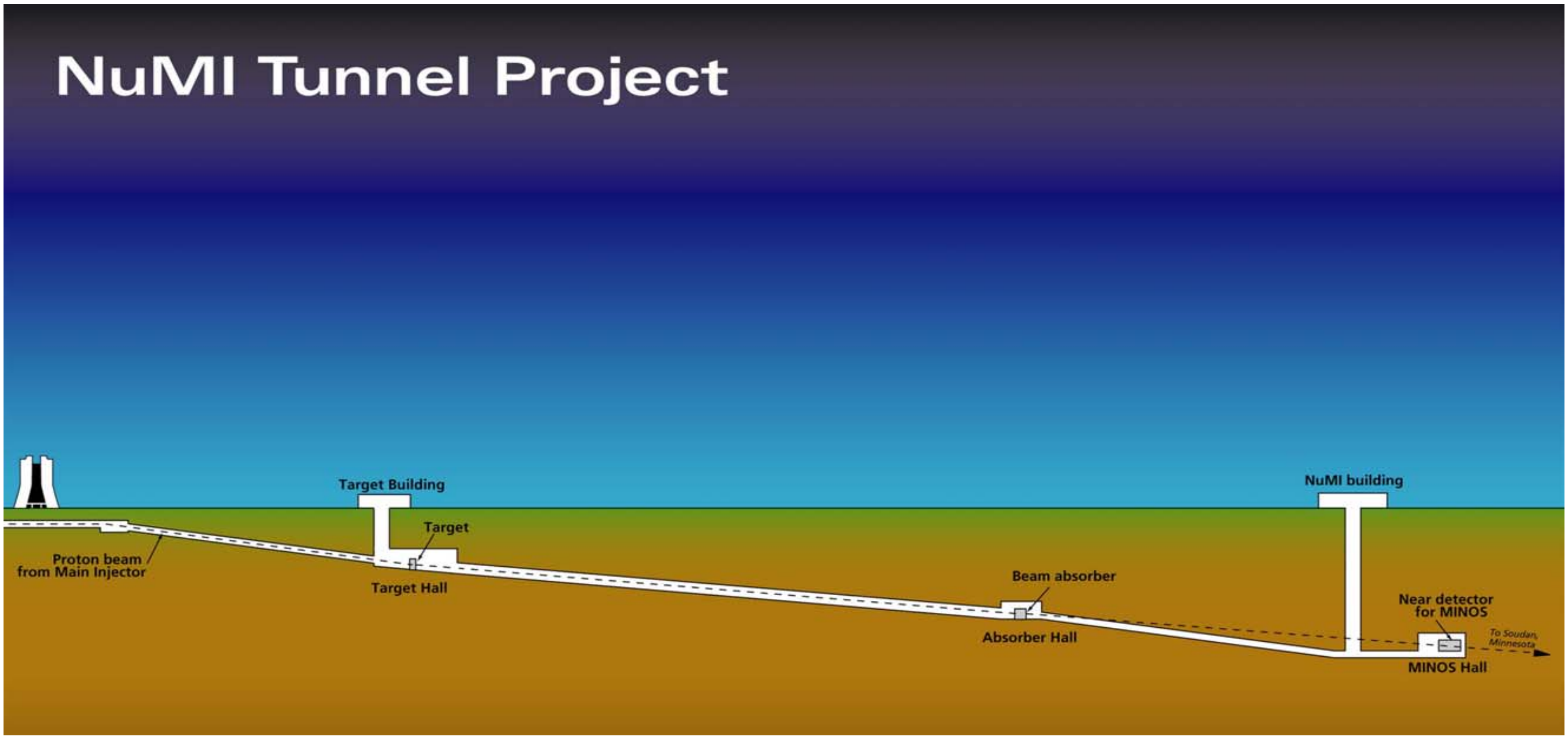


NuMI

MINOS

Underground Excavation Complete !

To do: outfit, surface bldg., install



677 m decay pipe

Target

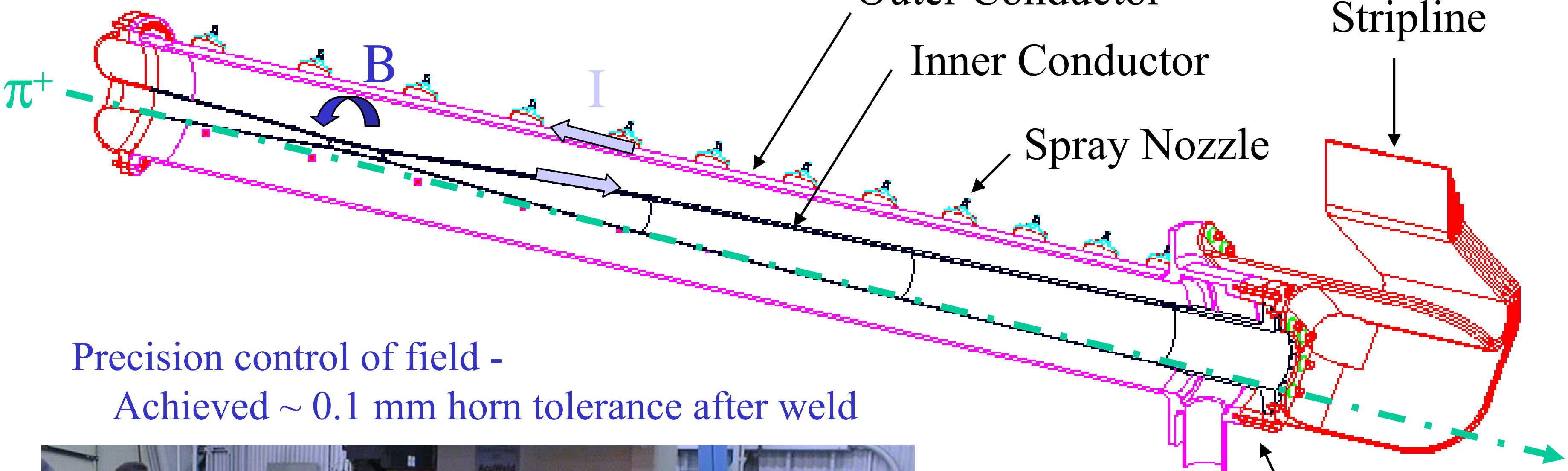
Near Detector

Status of NuMI Tunnel

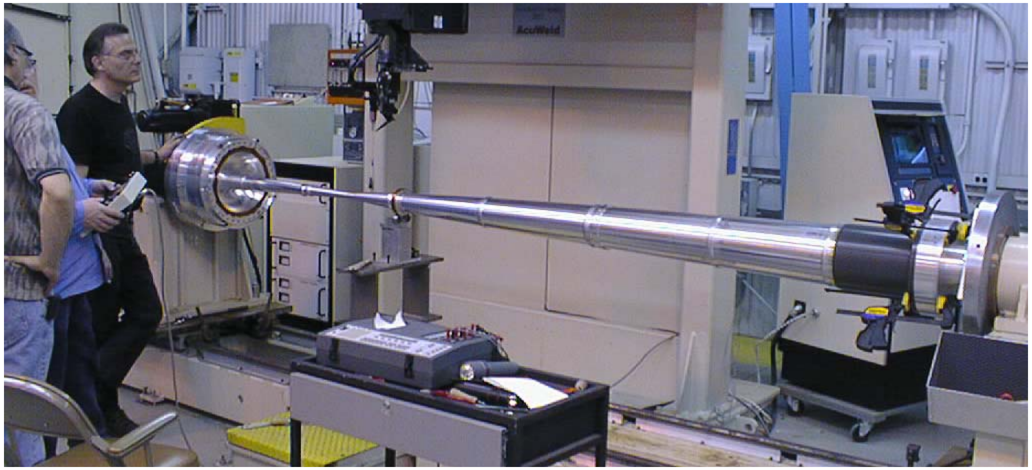
Decay pipe is finished and encased in concrete

Magnetic Horns

π focused by toroidal field between conductors



Precision control of field -
Achieved ~ 0.1 mm horn tolerance after weld

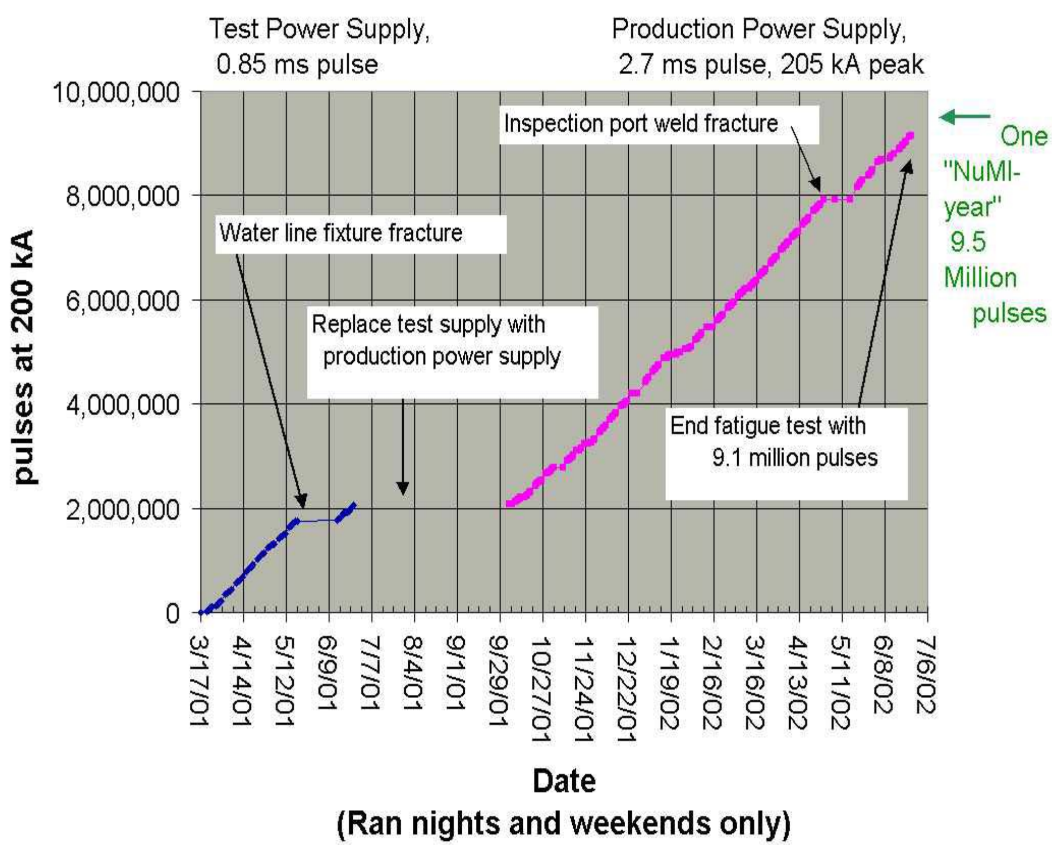


NuMI
MINOS

NuMI Horn1

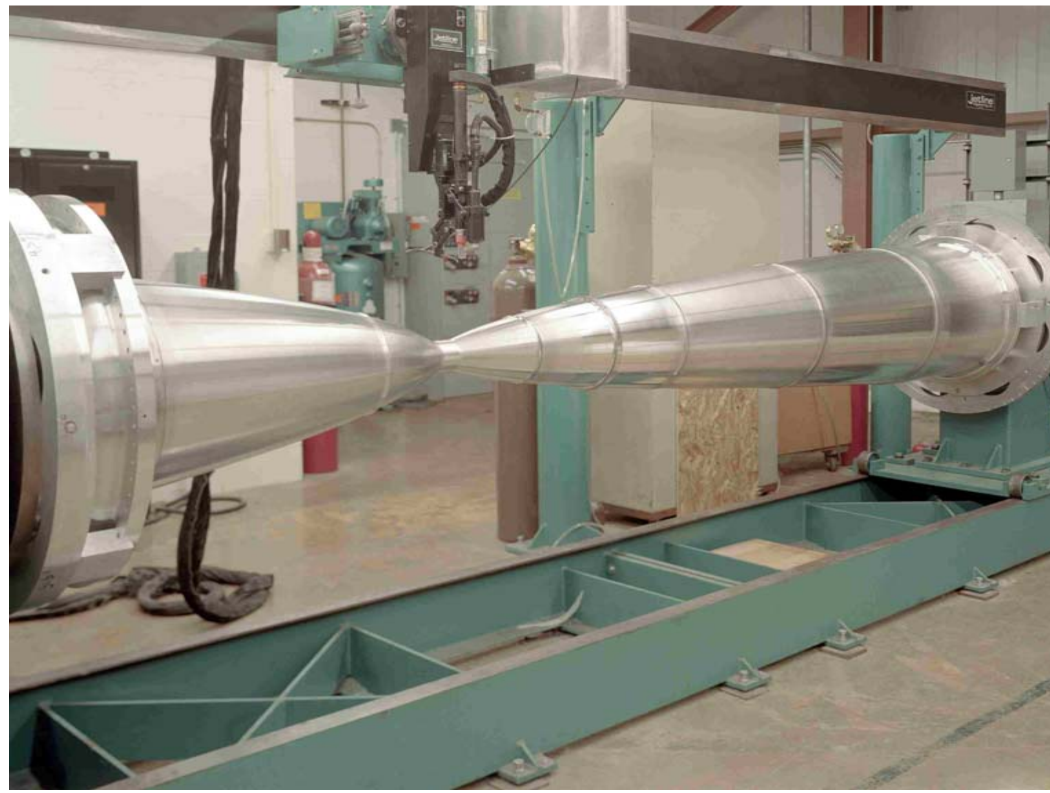
1st Horn under test

1 year worth of pulses



Horn 2 nearing completion

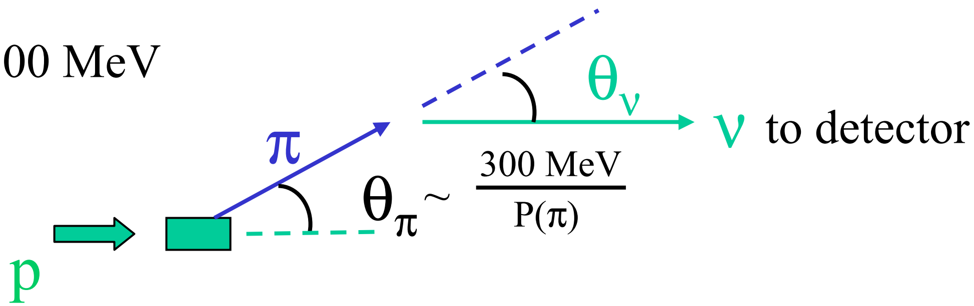
Initial weld samples



Final horn being welded

π^+ Production, Focusing, Decay

$P_t(\pi) \sim 300$ MeV

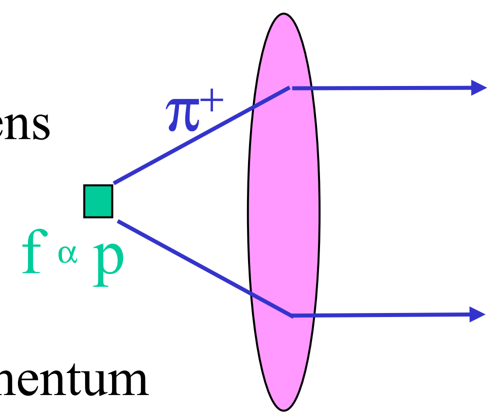


$$E_\nu \sim \frac{0.43\, E_\pi}{1 + \gamma_\pi^2 \theta_\nu^2}$$

$$\text{Flux} \sim \frac{\gamma_\pi^2}{(1 + \gamma_\pi^2 \theta_\nu^2)^2}$$

- Without focusing, flux to detector is only ~1/25 of flux in pion direction

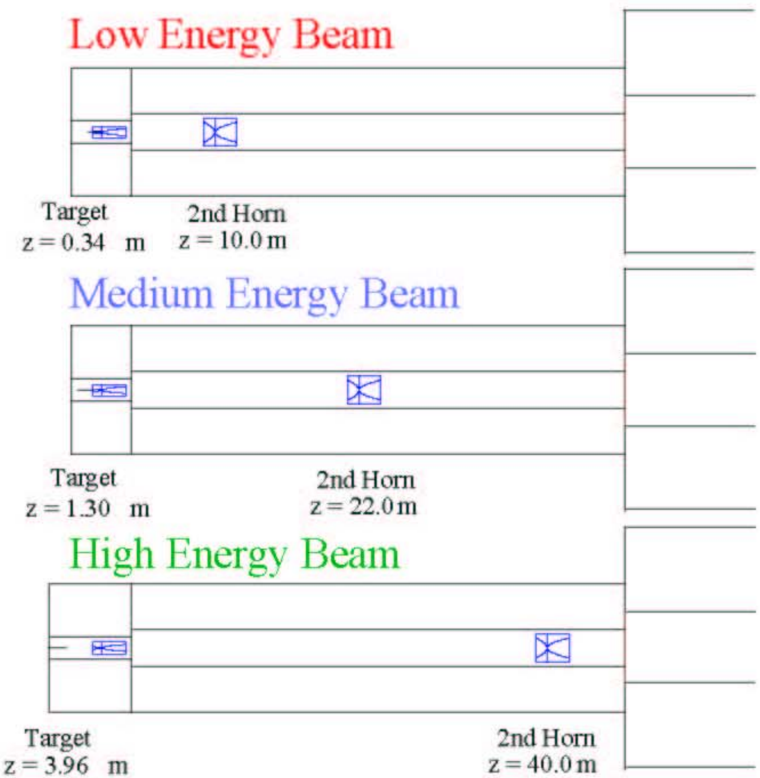
- With a parabolic shaped horn inner conductor,
  B dL (i.e. p_t kick) is linear with radius -> lens

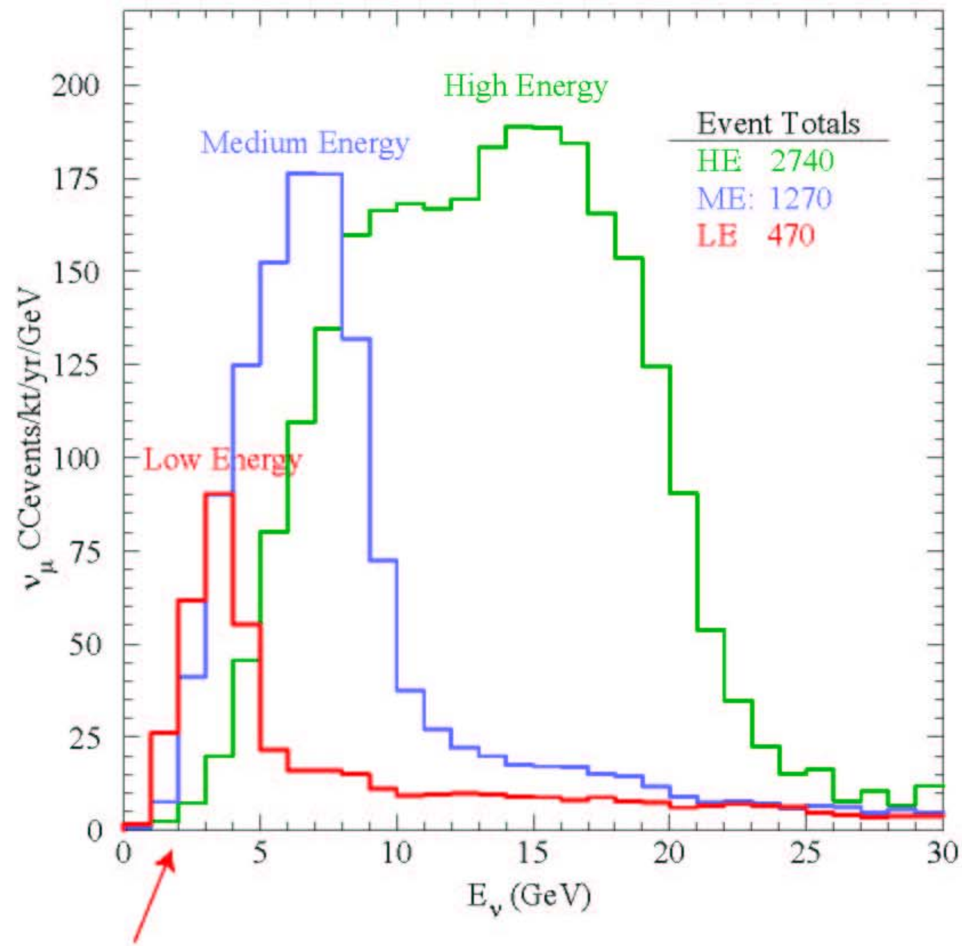


- The focal length is proportional to p:
  choice of target to horn distance selects momentum

- π focused parallel by horn 1 go through hole in horn 2;
  somewhat under or overfocused π are focused by horn 2

Different ν spectra obtained by moving target and 2^{nd} horn





MINOS on-axis: Low energy beam selected to start

Likely NuMI Schedule

- The Underground (tunnel, caverns, and shafts) contractor will finish mid-November of this year (2002)
- Surface buildings, outfitting take about 1 year
- Installation of beam technical components and Near Detector take about 1 year

First beam on NuMI target ~ 11/04

Advantages of off-axis beam

NuMI-MINOS is designed as broad band oscillation ν_μ disappearance search facility, has much higher reach in E_ν for its L than current knowledge would require (for ΔM^2=0.003 eV^2, 1st osc. node at 735 km is at 2 GeV)

@2GeV, (off-axis ME / on-axis LE):

1) gives twice the ν_μ beam flux

2) ν_e beam background / ν_μ beam reduced by factor 2-3 at source
(and much of ν_μ oscillate away, reducing mis-ID b.g.)

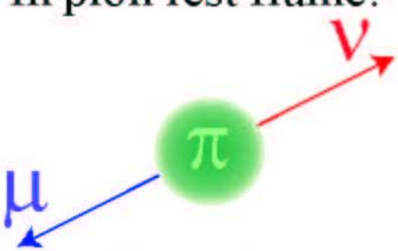
3) High energy tail in spectrum greatly reduced
NC feed-down background greatly reduced
Events above ν_τ CC threshold, and thus ν_τ -> *e* b.g., greatly reduced

4) ν_e beam background mostly from muon decay
(easier to predict than kaon decay background)

Decay kinematics

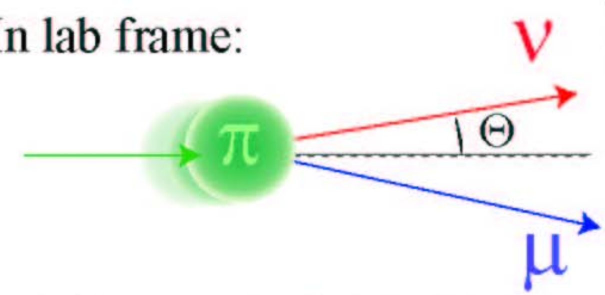
of perfectly focused pions

In pion rest frame:

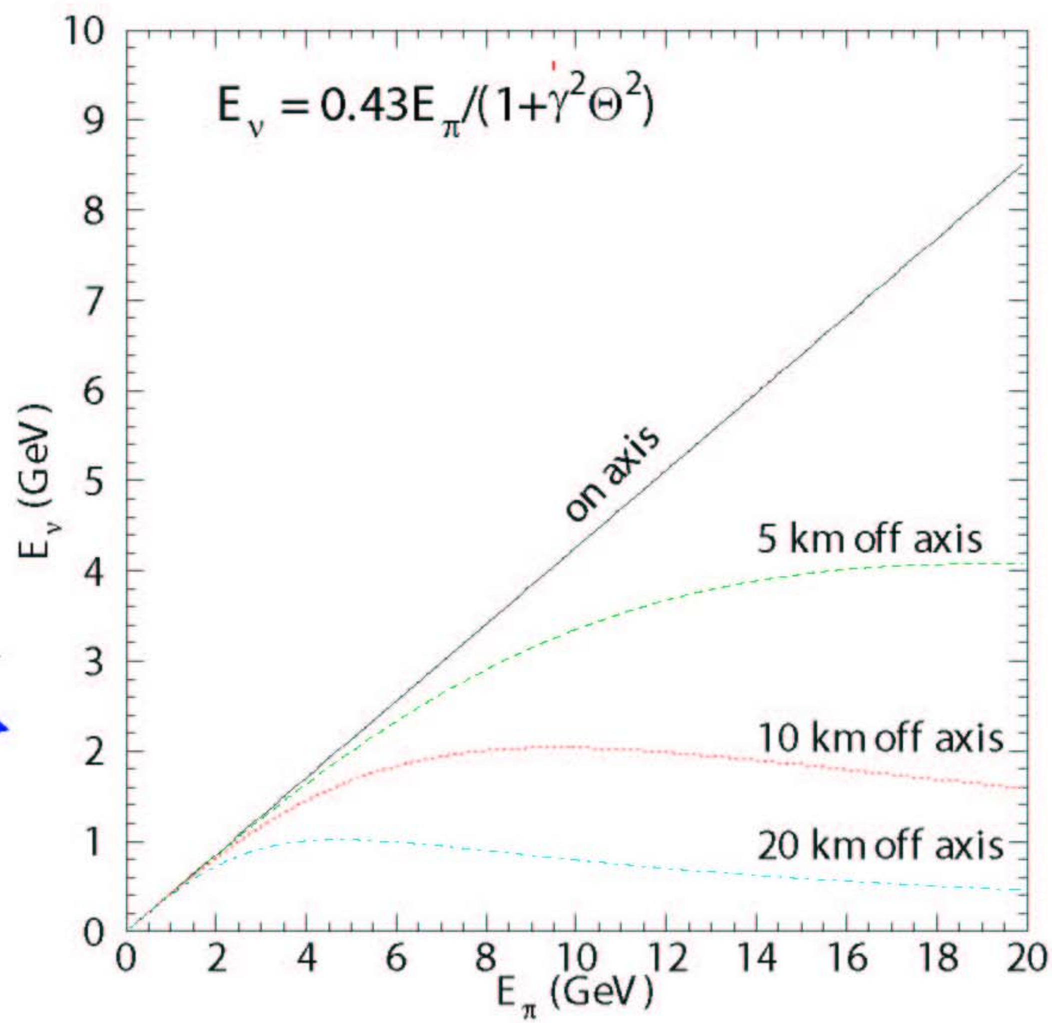


Neutrino and muon energy completely determined

In lab frame:

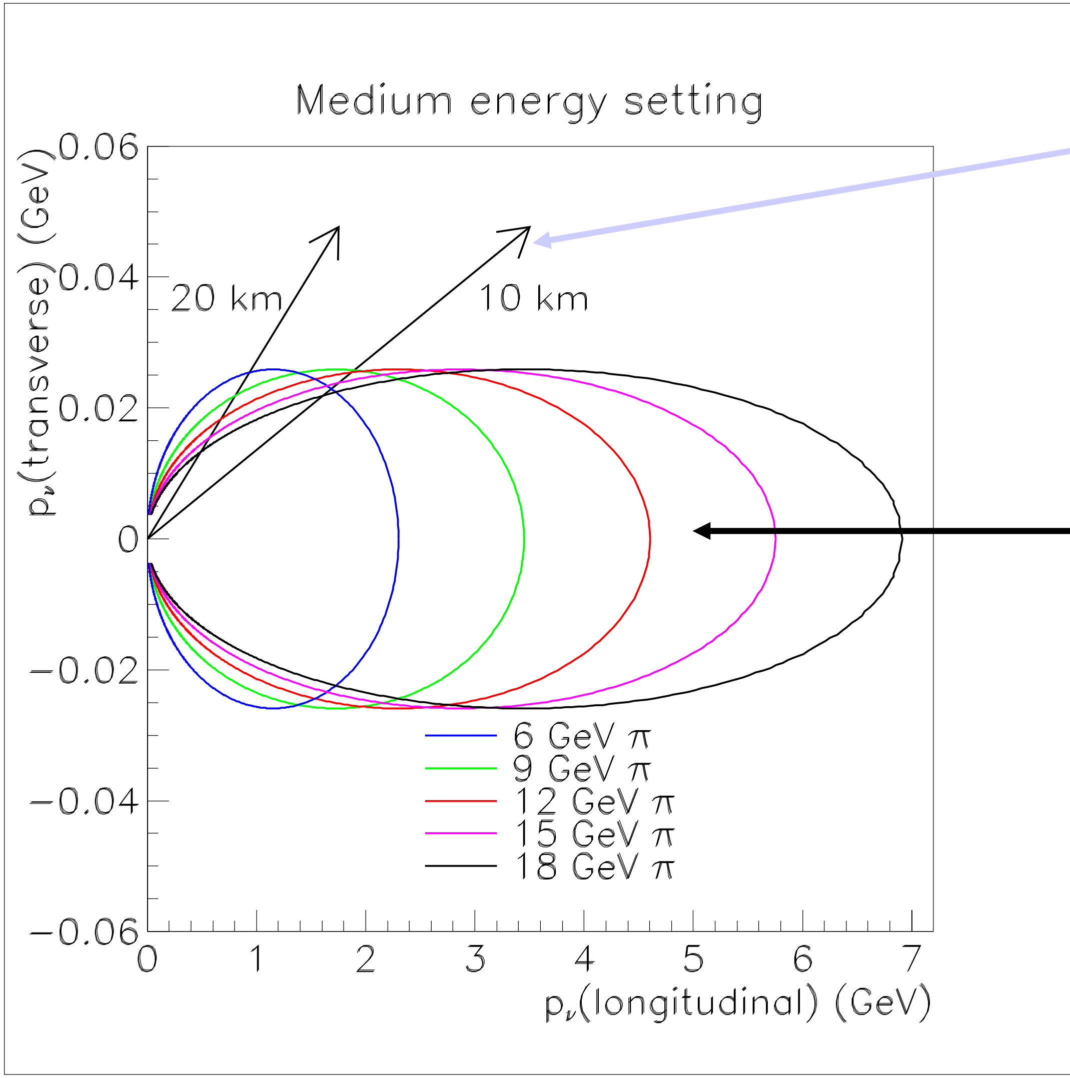


Neutrino energy depends on boost and angle to boost direction



Two body decay kinematics

of perfectly focused pions



At this angle, 15 mrad, energy of produced neutrinos is 1.5-2 GeV for all pion energies → very intense, narrow band beam

'On axis': $E_\nu = 0.43 E_\pi$

$$p_L = \gamma(p^* \cos\theta^* + \beta E^*)$$
$$p_T = p^* \sin\theta^*$$

What are P_t scales?

Does this magic really work?

P_t max for ν from pi decay is 30 MeV/c

Hadronic production of pions peaks around P_t of 200 – 300 MeV/c

Horn focus reduces this to ~ 10 MeV/c over some momentum range, so that this off-axis "magic" can help, and P_t (pion) < P_t (decay).

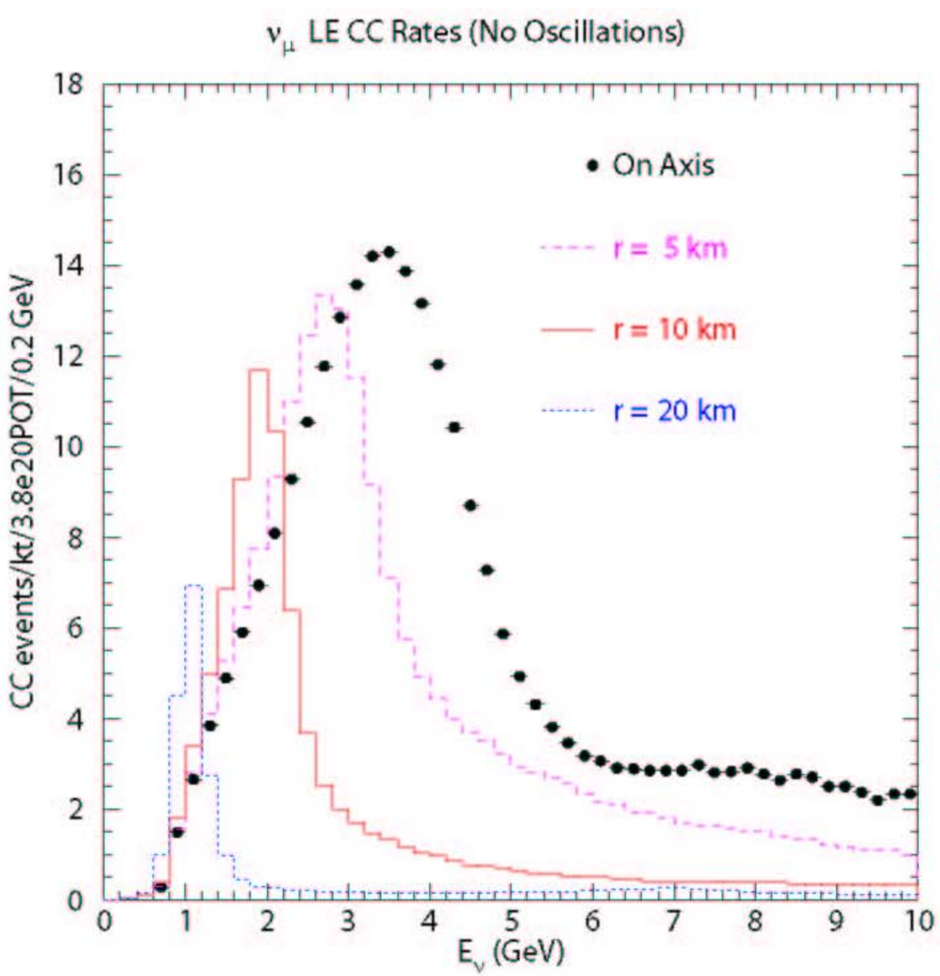
Does induce significant smearing, need full M.C. to understand beam

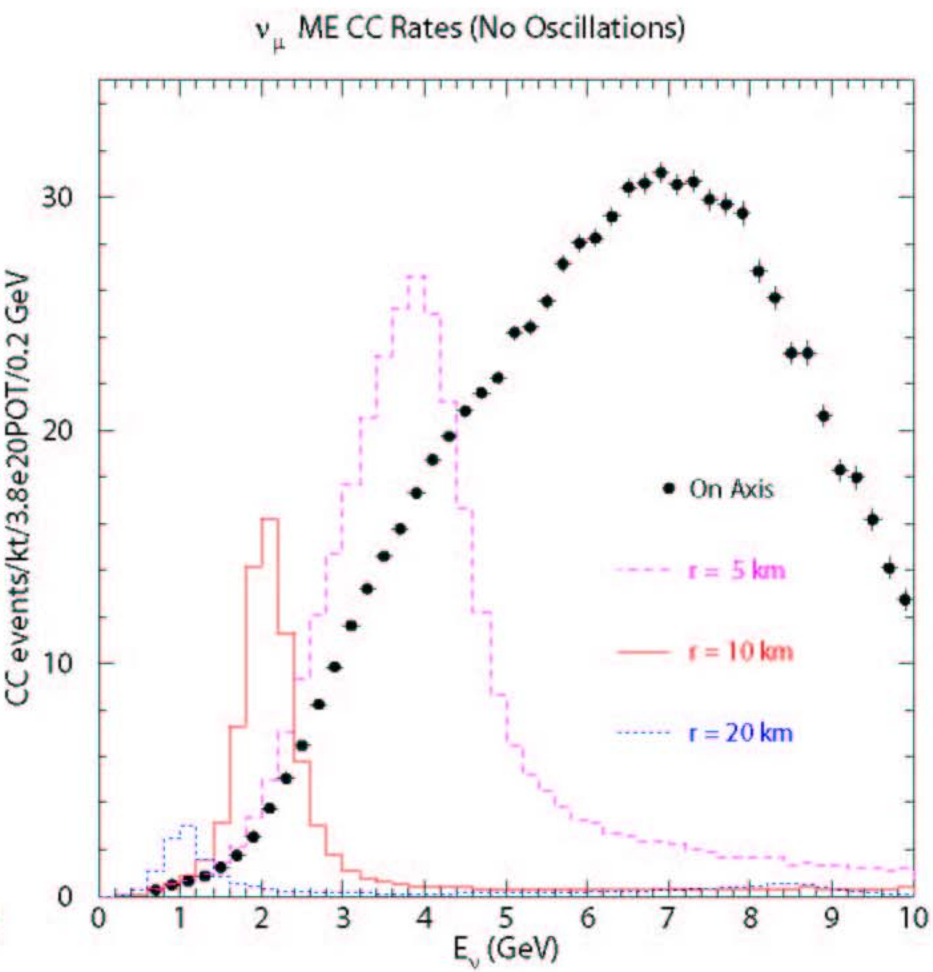
At other momentum ranges, pion P_t dominates decay P_t

(multiple scattering ~ few MeV/c)

For reference, Beamline geometry aperture ~ 10 mr at low momentum
effective aperture becomes smaller at high momentum

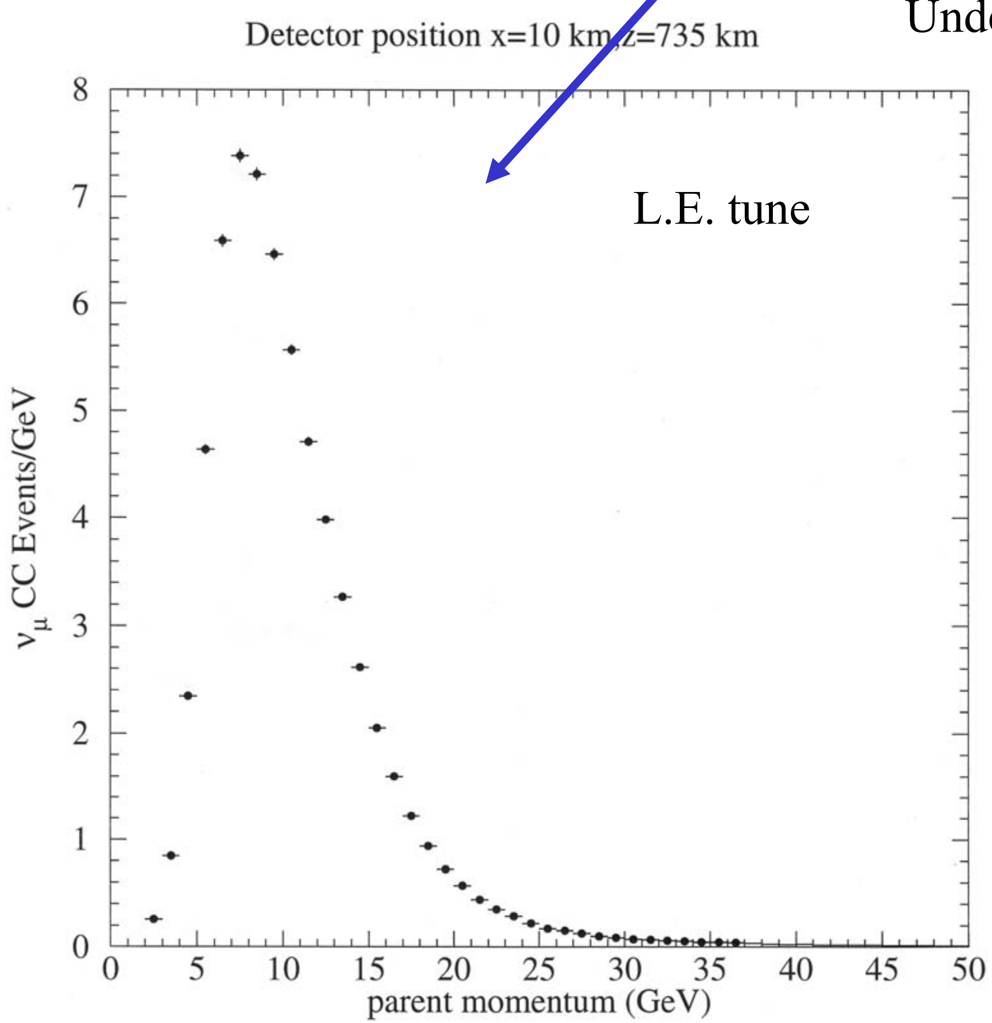
ν_μ spectra moving off-axis
(unoscillated, GEANT M.C.)

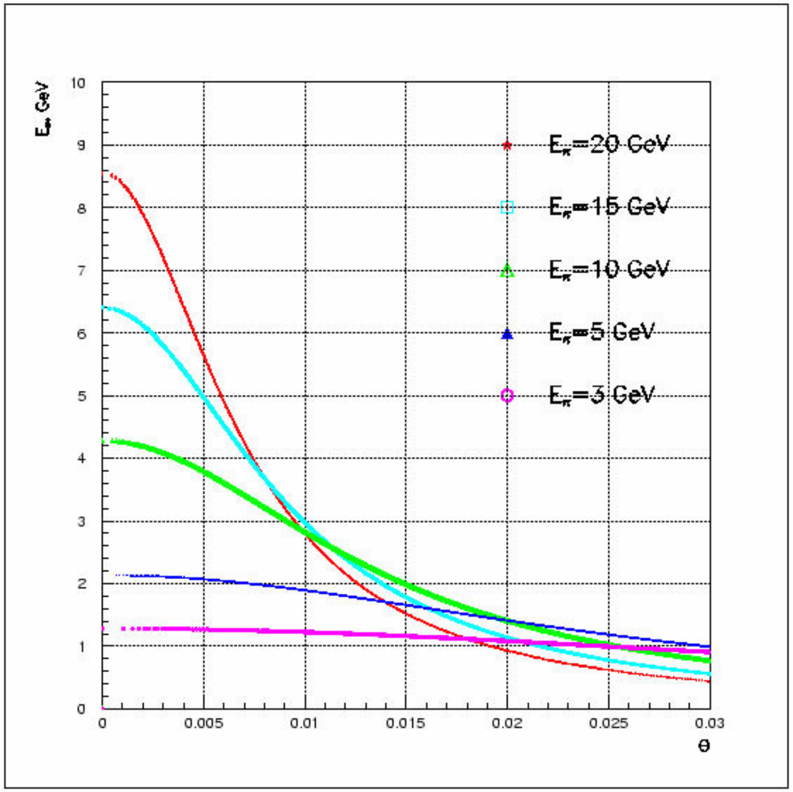




What parent pions are actually contributing?

Understand from pi production, focus, flux fact.



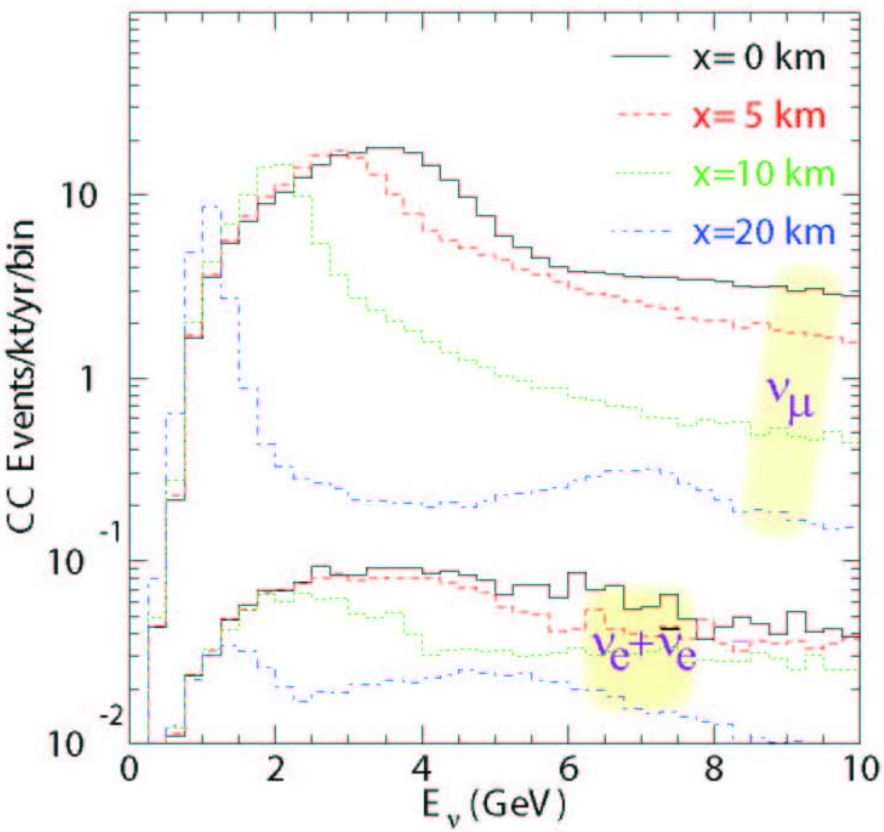


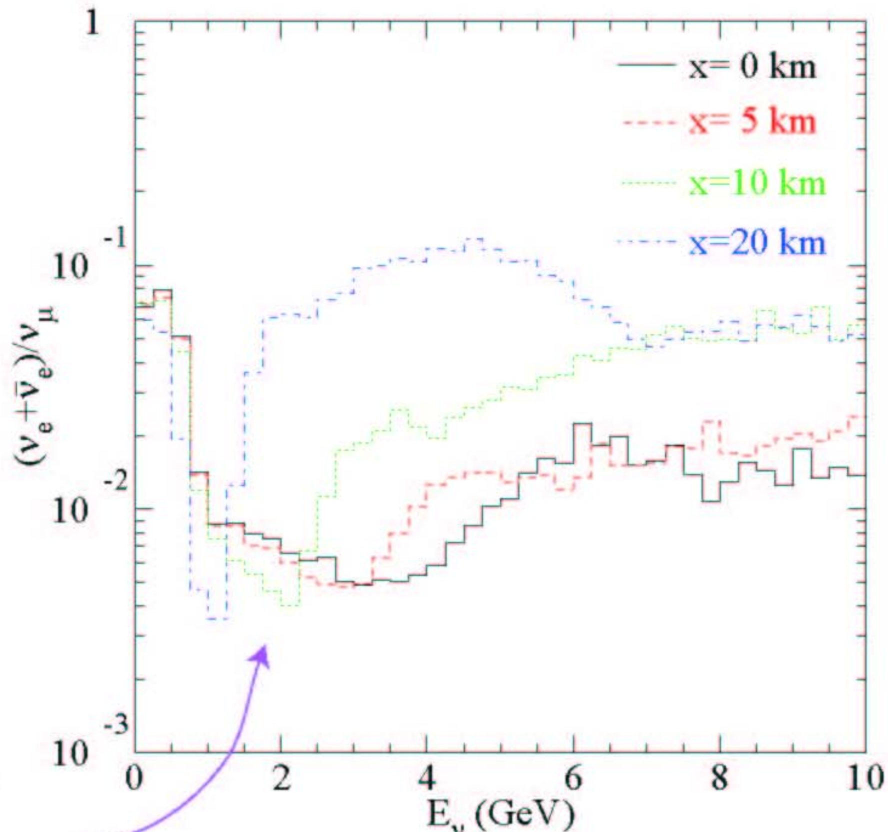
$$Flux = \left(\frac{2\gamma}{1+\gamma^2\theta^2} \right)^2 \frac{A}{4\pi z^2}$$

Quantitatively

- Solid angle for off-axis ~ $\gamma^2/(1 + (\gamma\theta)^2)^2/L^2$
- E_ν (and hence x-section) ~ $\gamma / (1 + \gamma^2 \theta^2)$
- Compare with γ^2 / L^2 and γ for 0^o
- For optimum, $\gamma\theta \sim 1$
- For NuMI, advantages are energy compression and shift to better match to L and Δm^2
- But per pion , neutrino event yield is 8 times smaller
- Once you choose your location, you no longer have much flexibility to change beam parameters

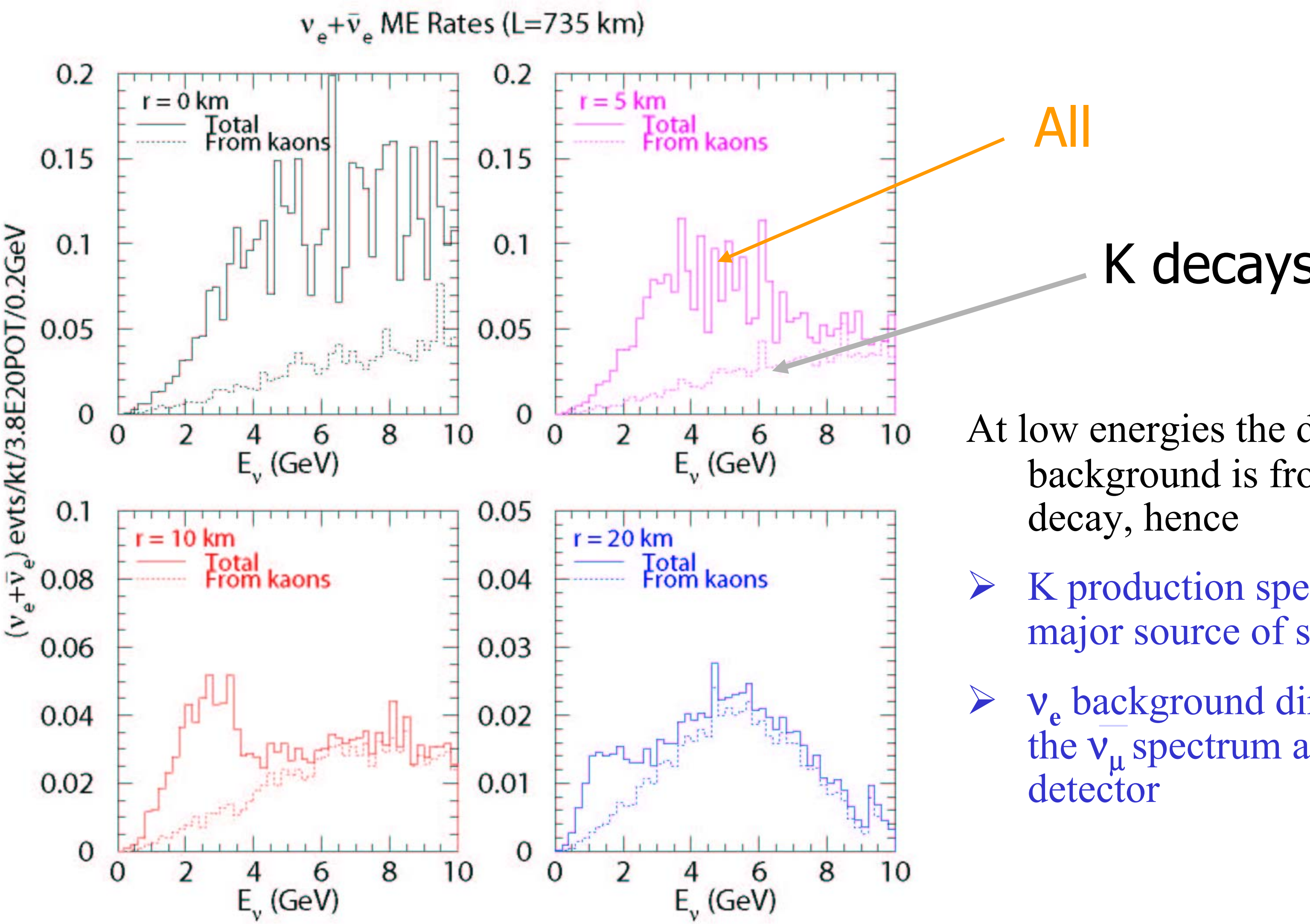
ν_e rates moving off-axis (L.E.)





0.4 - 0.5% in signal region

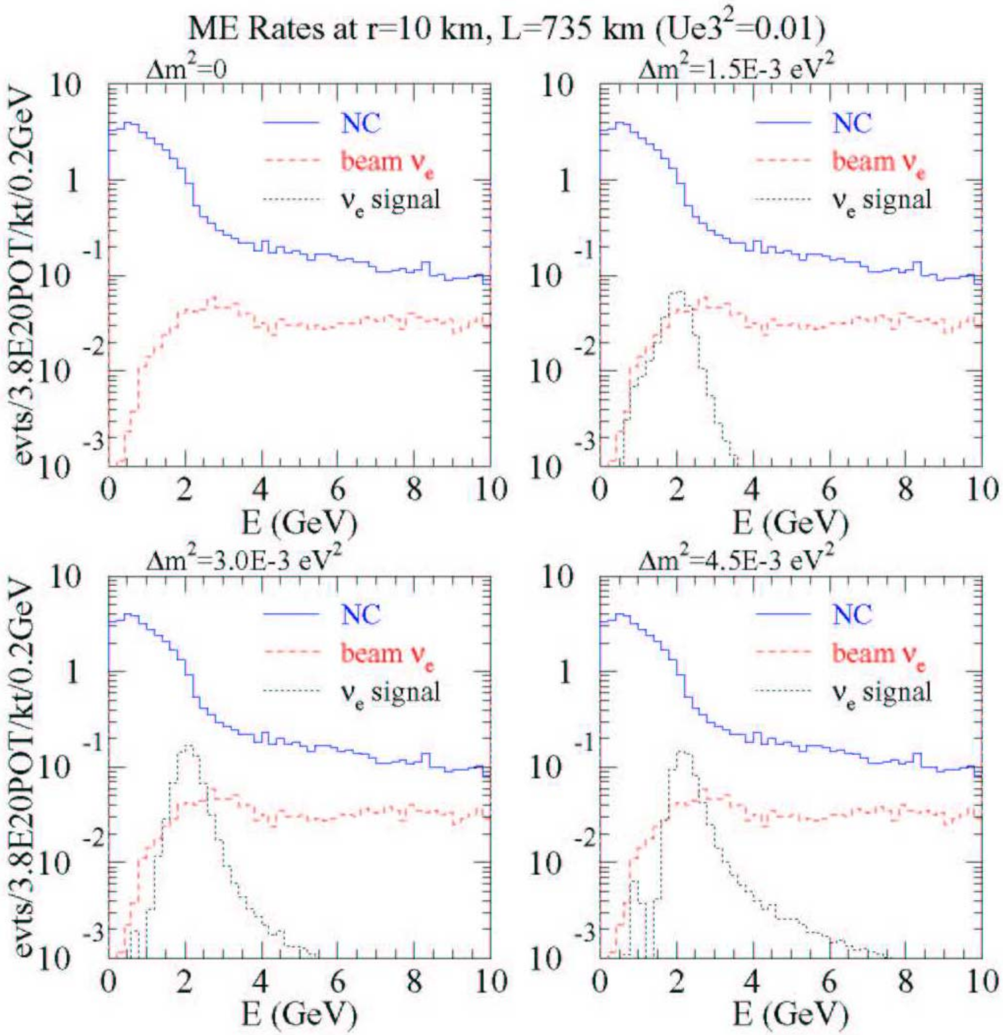
Sources of the ν_e background



At low energies the dominant background is from $\mu^+ \rightarrow e^+ + \nu_e + \nu_\mu$ decay, hence

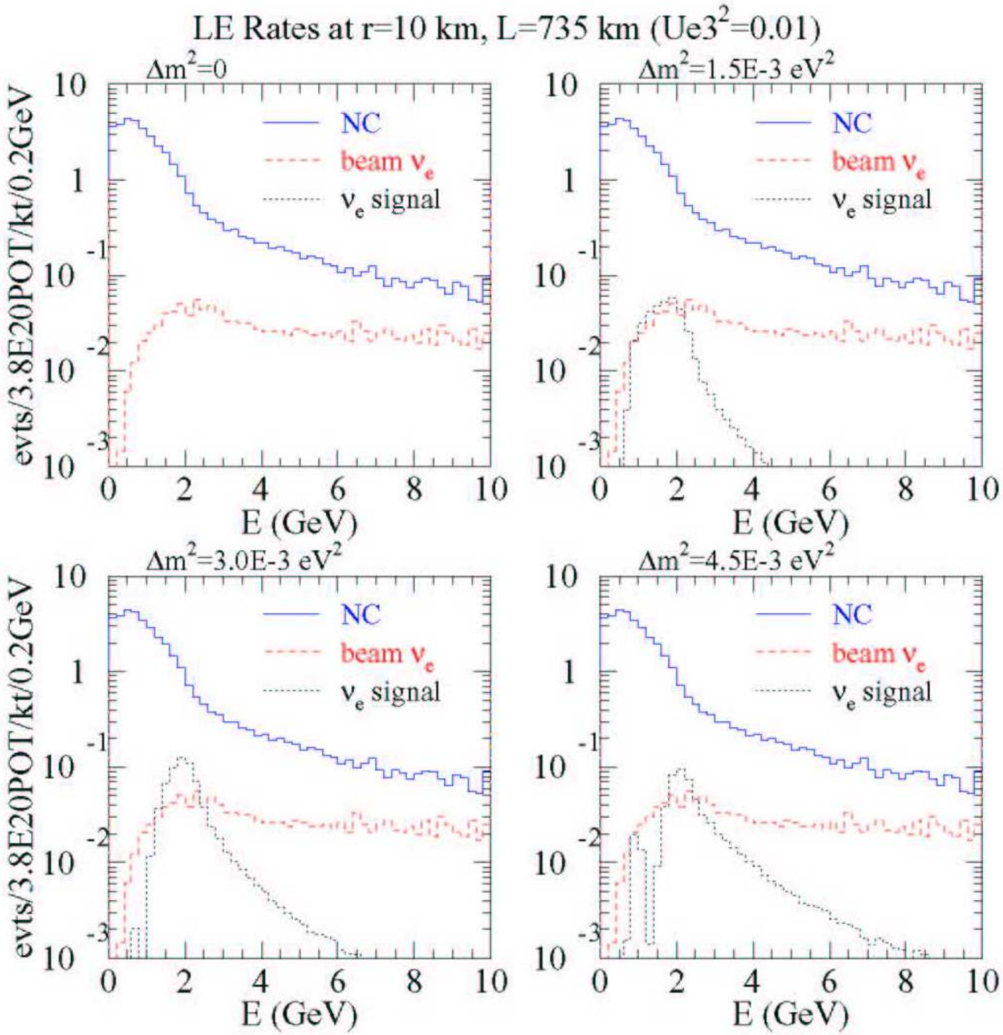
- K production spectrum is not a major source of systematics
- ν_e background directly related to the ν_μ spectrum at the near detector

N.C. rates off-axis (M.E.)



Detector will require good NC rejection

N.C. rates off-axis (L.E.)

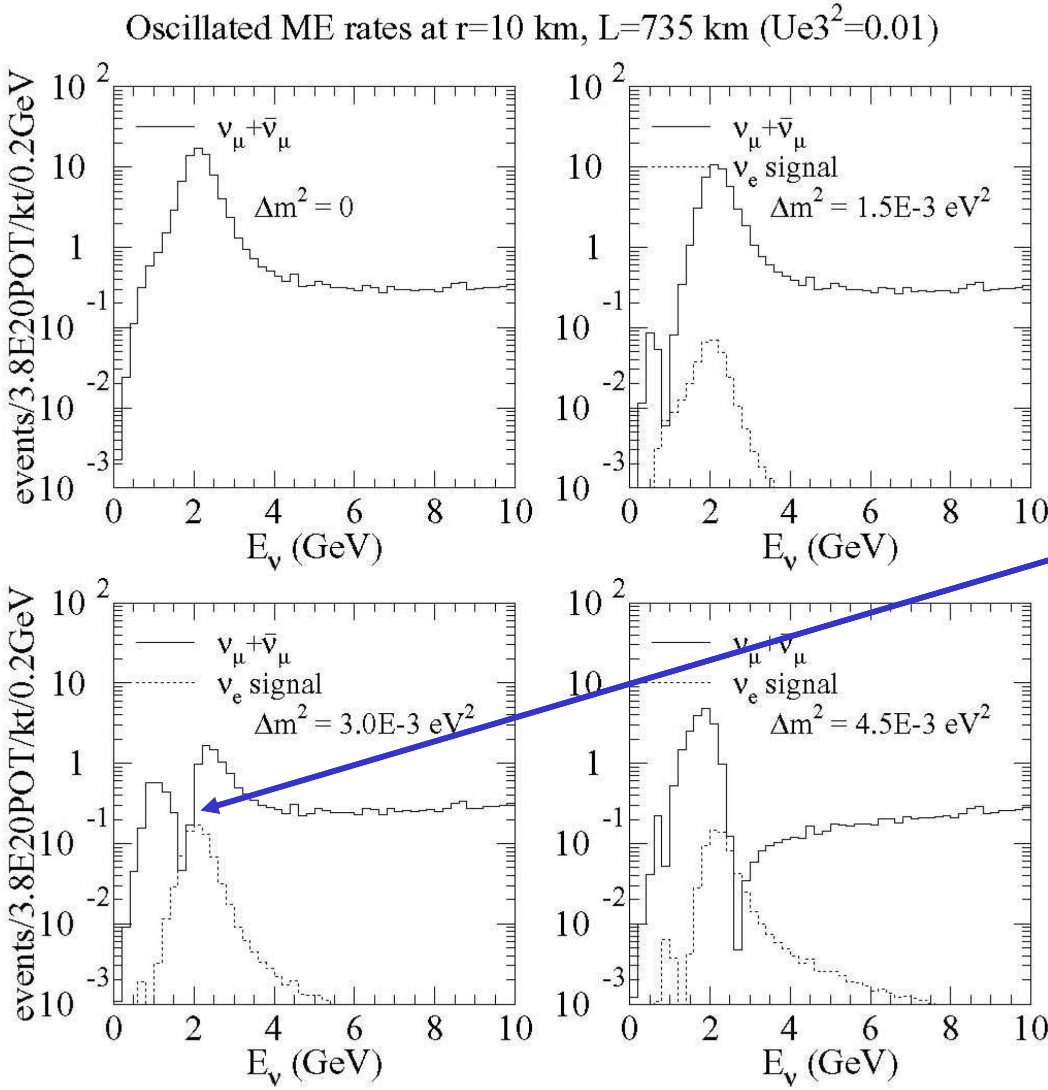


M.E. off-axis
looked a little better
than this L.E. off-axis beam

NuMI

MINOS

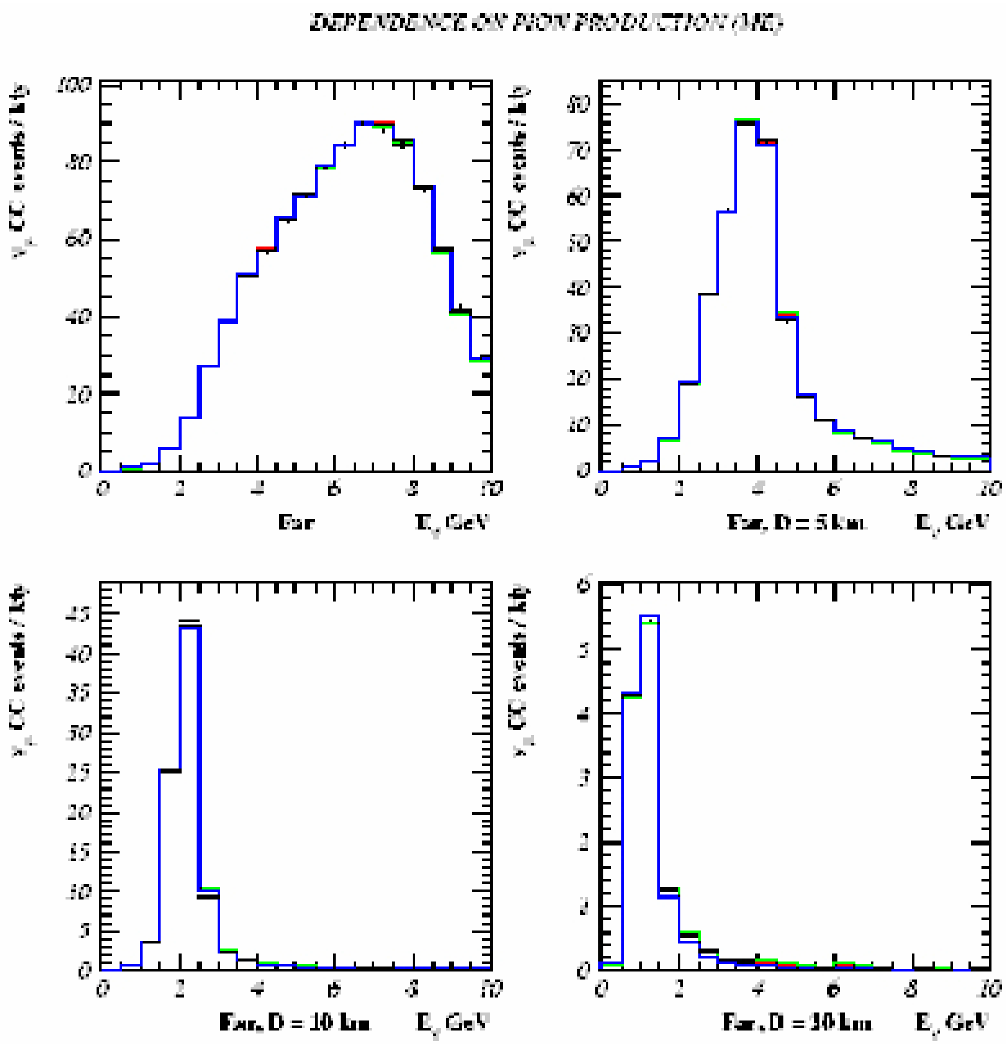
ν_μ oscillated spectrum



Mis-ID from ν_μ CC can get really small,

since most of ν_μ may have oscillated away

Far Detector spectra from Near Detector measurements

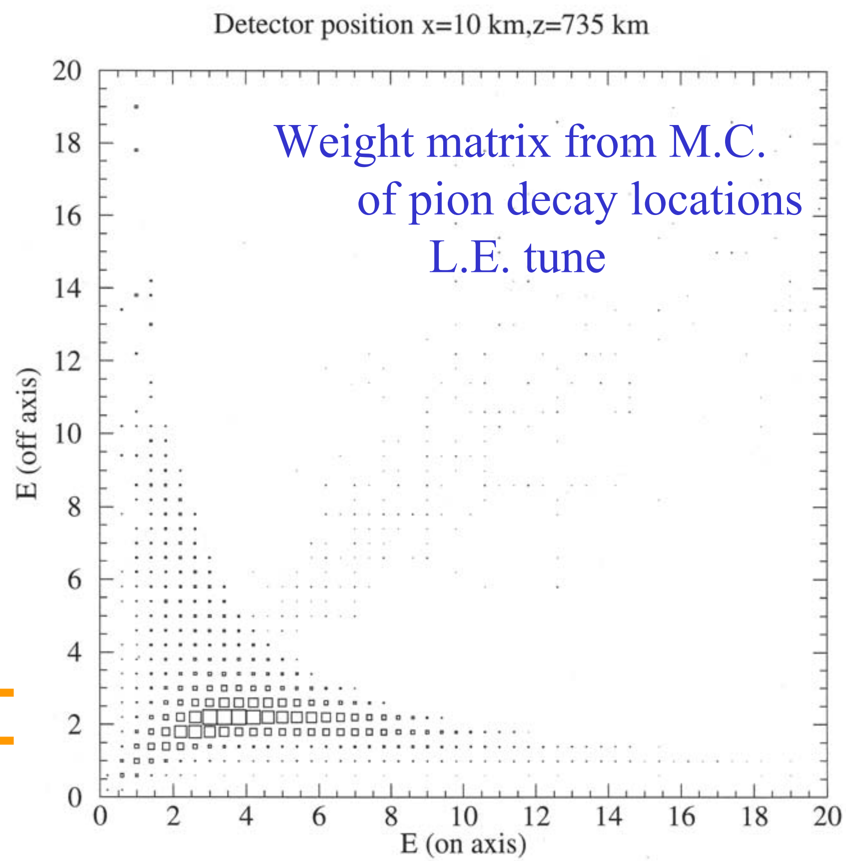


Event spectra at far detectors located at different positions derived from the single near detector spectrum using <u>different particle production models.</u>

Four different histograms superimposed

Total flux
is predictable
to 2 %

How does prediction of off-axis spectrum work?



Output the Far Off-axis Spectrum

Input the Measured Near Detector Spectrum (for now, other hadron production models)

Raw production model ν_μ prediction.
Then near detector constrained !

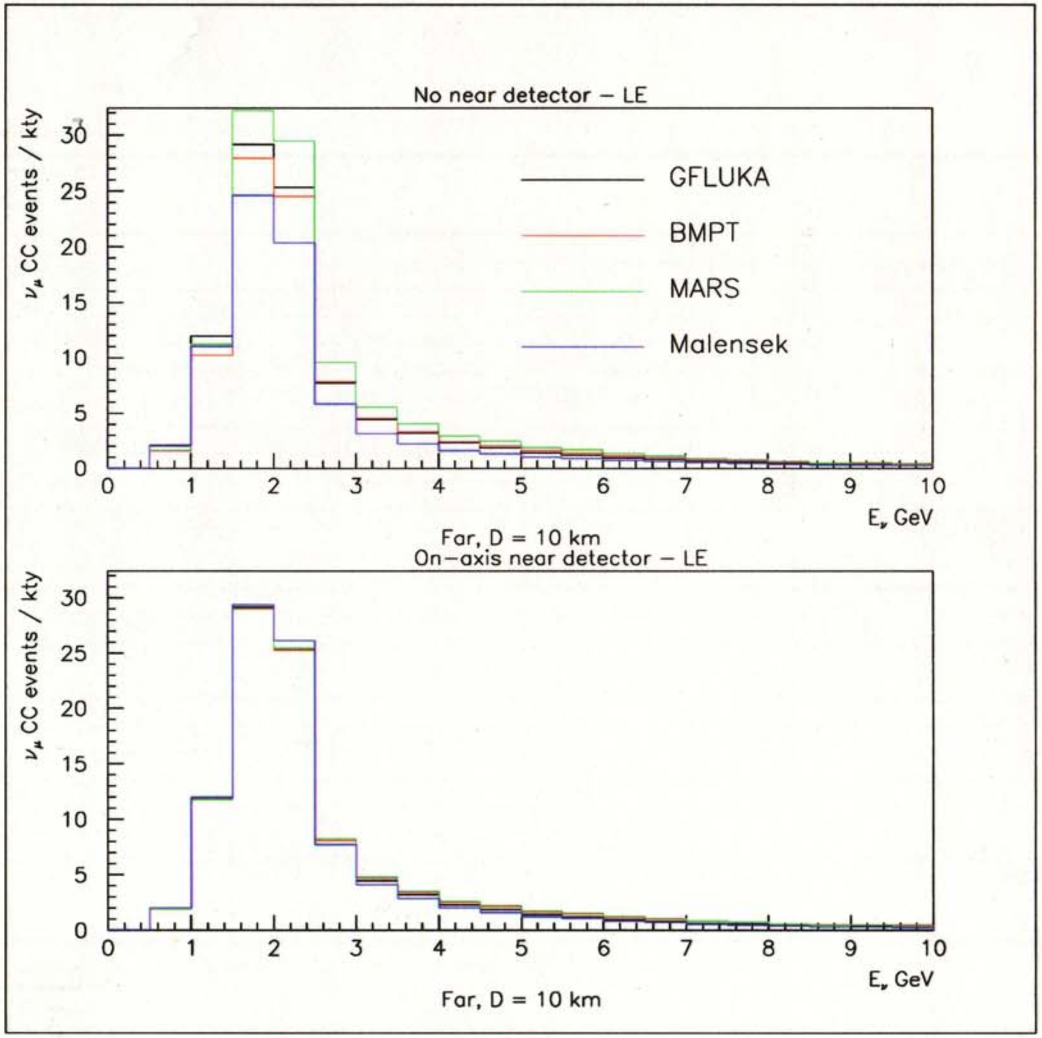
Low energy option

Predictions for far detector spectra (NuMI beamline, LE, L = 735 km), D = 10 km off axis.

- On absence of any near detector: ~25% uncertainty.

- With an on-axis near detector (*M* matrix derived from each model):

GFLUKA: 74.2 events 1-3 GeV,
BMPT: 74.3 events,
MARS: 74.7 events,
Malensek: 75.4 events.

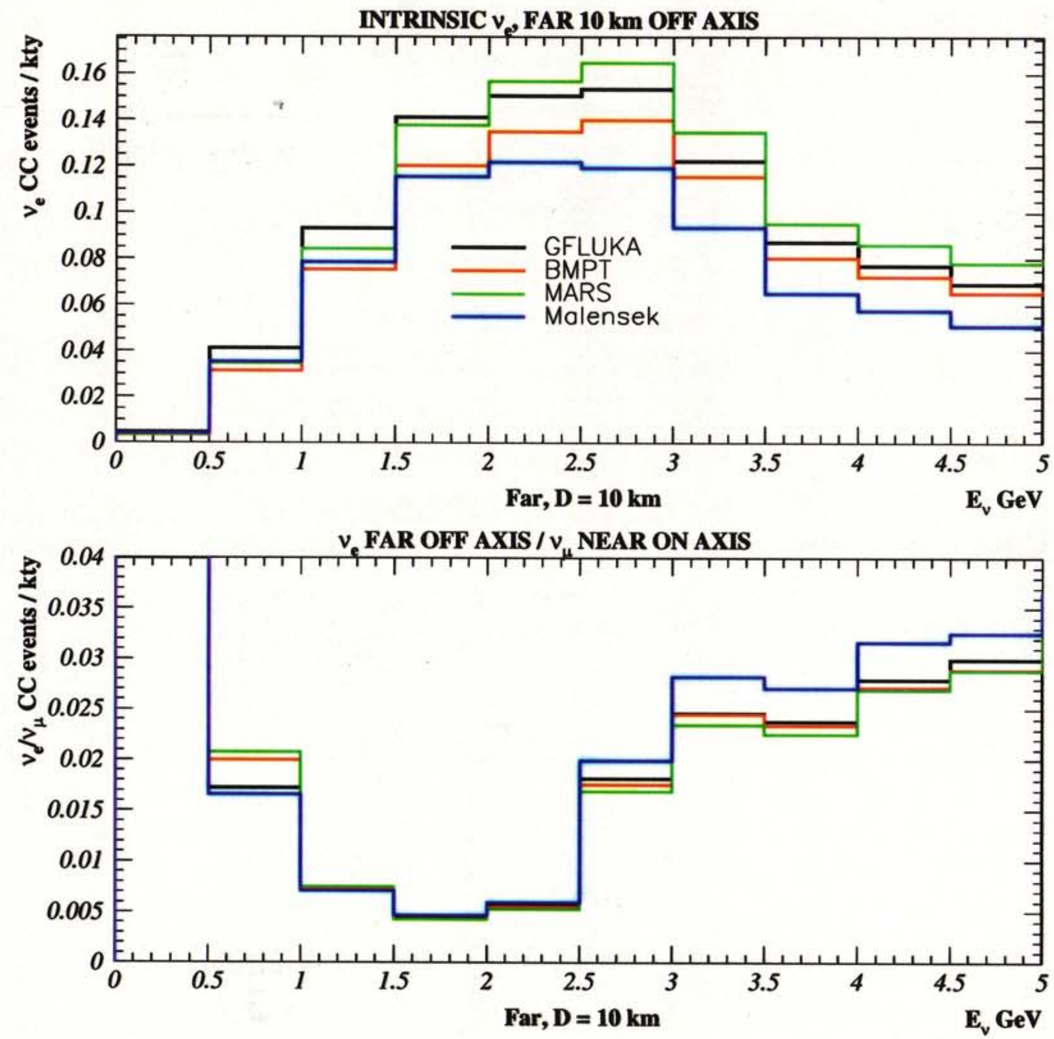


A first attempt to extrapolate off-axis far ν_e from near ν_μ flux

Hadron production related uncertainties are minimized by using ν_μ information from the on-axis near detector.

E.g., for $1 < E_\nu < 2.5$ GeV, the total rate is predictible to $\sim 6\%$.

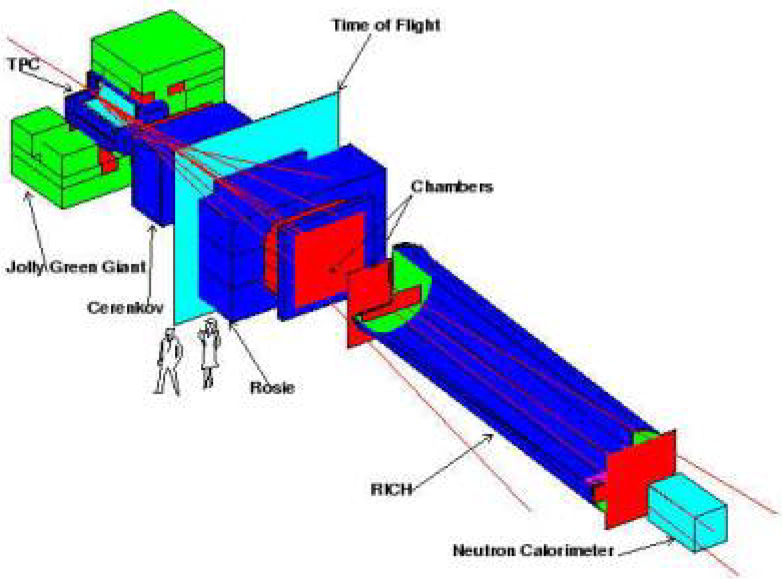
Here, a Near-ν_μ-to-far-ν_e correlation matrix M' can be evaluated $\rightarrow$ possibly a still more accurate prediction.



What about systematics from poorly known neutrino cross sections ?

MIPP

Main Injector Particle Production Experiment (FNAL-E907)



MIPP will run at FNAL in 2003

- Measure 120 GeV proton-carbon -> π, K, …
- Good precision, ~ 2%
- NOT single arm spectrometer
  - *get all P_t, P*
  - *acceptance correction easier*
- Use actual NuMI target

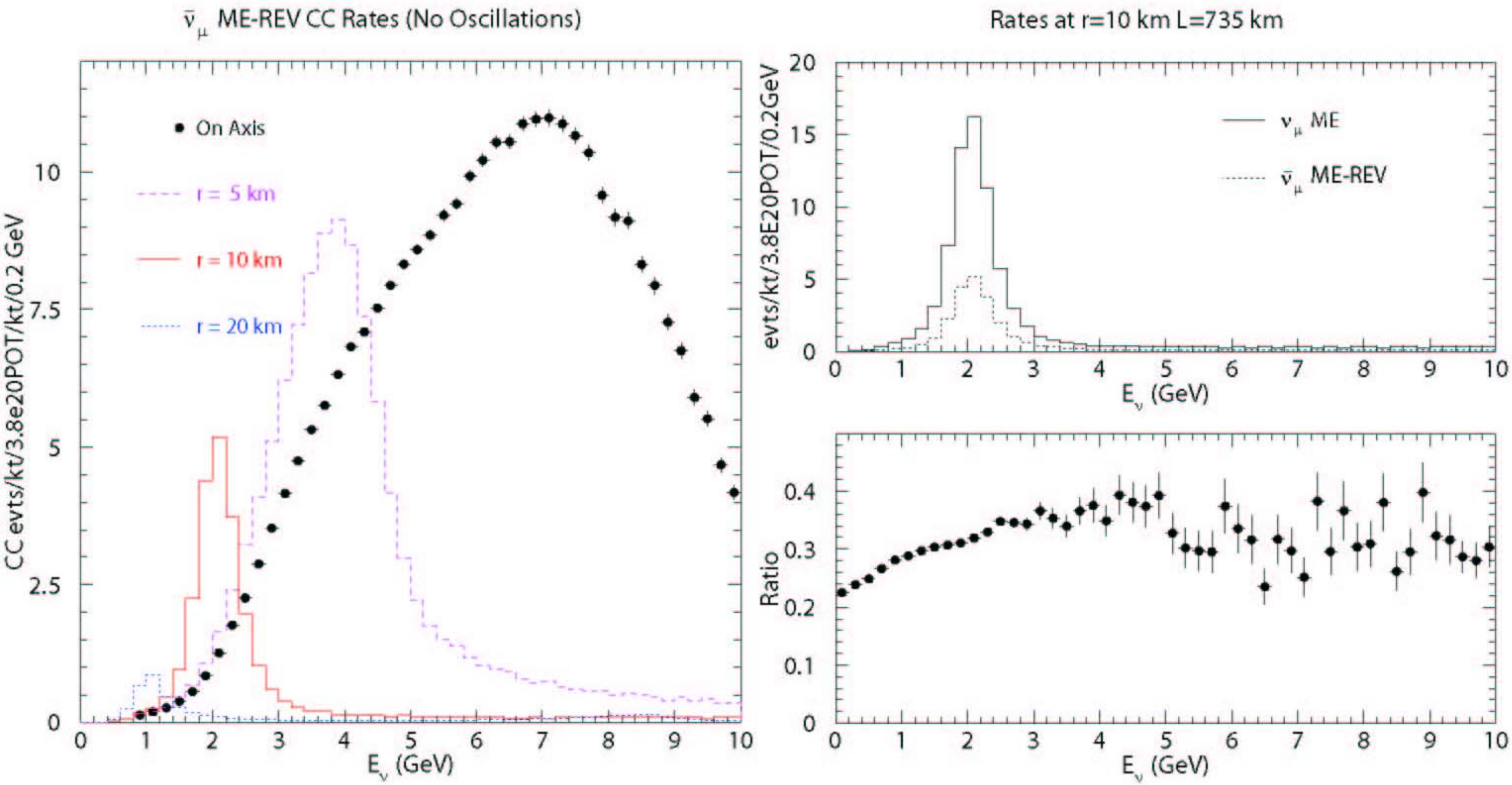
With NuMI precision horns and above MIPP hadron production measurements, will make very good prediction of ν flux in near detector

- *have already measured excellent magnetic field quality in 1st horn*

With well understood near detector, and above flux predictions, will measure neutrino cross sections to a few %

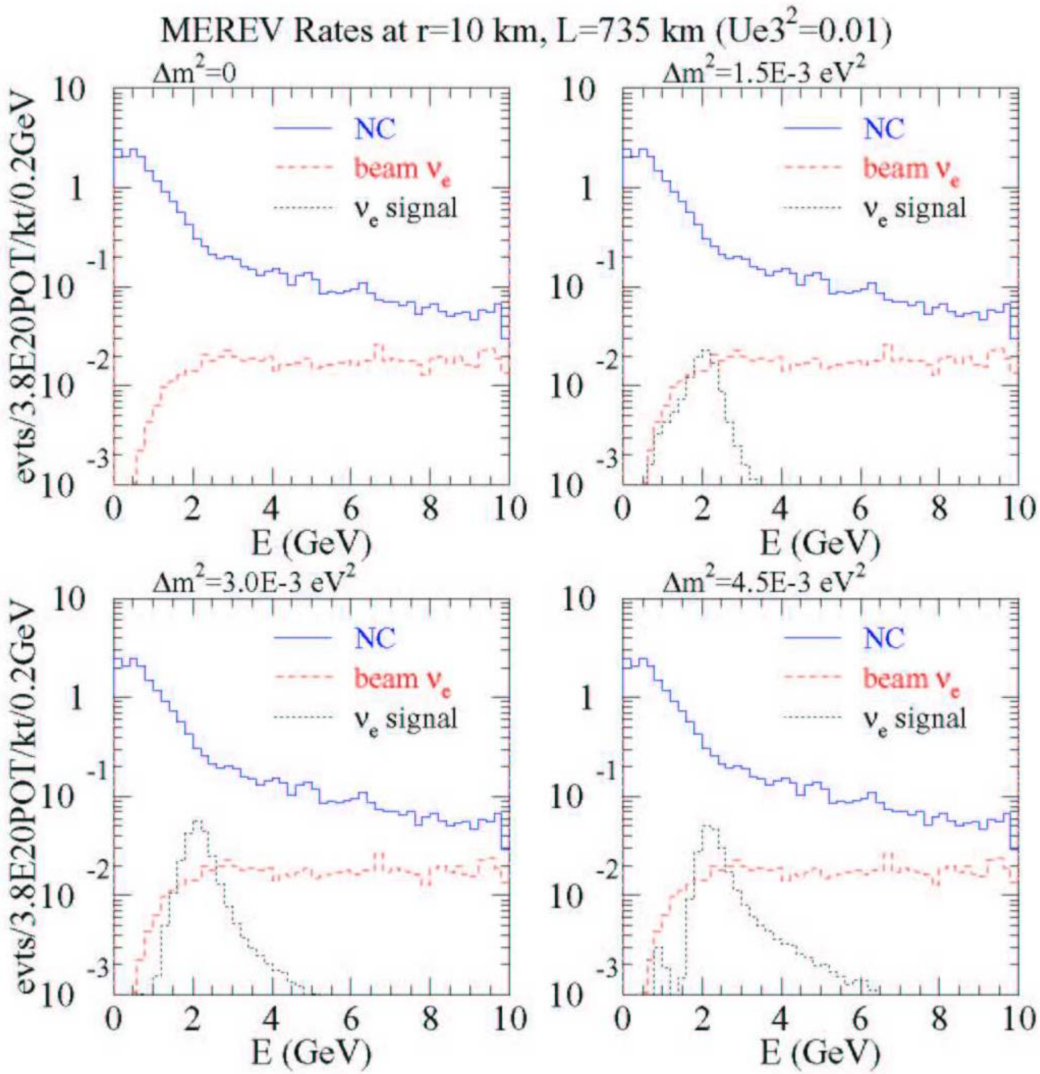
-> want near detector of same material as far, but location of near detector may not be important

Anti-neutrino beam by reversing horn current

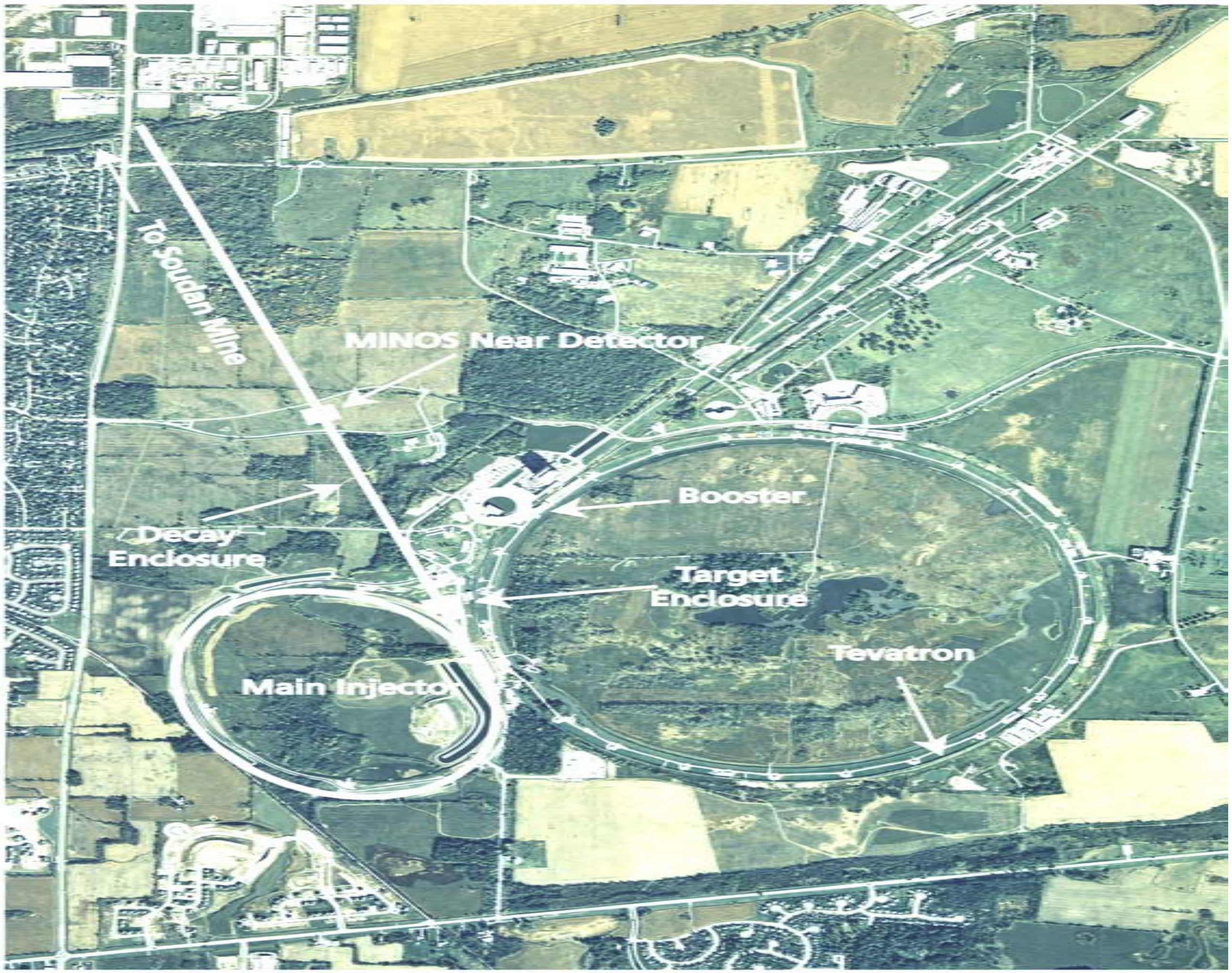


Slightly less flux, bigger hit in anti-neutrino cross section, ~ 1/3 as many events !

Anti-neutrino running backgrounds



Near Detector location options



Distance from present MINOS Near Detector to FNAL site boundary is 2 km.

Thus distant Near Detector at the appropriate angle is possible.

There appears to be <u>no requirement</u> for such a distant near detector.

Probably put N.D. in present cavern (on axis), or present transfer tunnel (off axis)

Near Detector Issues

Off-axis Near Detector may not be necessary for ν_e background estimate:

- pion flux (and hence muon flux) measured in on-axis ND
- muon flux checked directly in muon monitors
- K decays are minor contribution
- τ decays don't contribute in this energy range
- MINOS Near Detector can perform the required measurements

NC background estimate is more difficult

- the level of understanding required depends on its size
- off-axis Near Detector of same technology can measure this background
- the Far Detector spectrum does not have to be reproduced exactly

Both these backgrounds have much broader spectrum in far detector than the ν_e oscillation signal

Further Beam Optimization ?
(just some of my thoughts for discussion)

1. Optimum with existing horns is probably close to ME focus,
   has not been fine tuned
2. Probably want longer, narrower target; not studied yet
3. Change in horn shape not investigated, may give modest improvement
4. E907 MIPP experiment will measure target hadron production,
   will allow more precise optimization studies
5. Extrapolation of beam ν_e background deserves more detailed study
6. How cross section factors into extrapolation also needs study